AEROASSISTED COPLANAR TRANSFER FROM GEOSTATIONARY ORBIT TO LOW EARTH ORBIT

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Abstract: *Aeroassisted maneuvers use the atmospheric forces to change the trajectory and velocity of a spacecraft. Several studies in this area showed that a significant reduction in fuel can be achieved using this technique rather than an equivalent propulsive transfer. The aim of this paper is to demonstrate the simulation results of an aeroassisted maneuver between coplanar circular orbits, from a geostationary orbit to a low orbit. We adopted a spacecraft with a cubic body composed of two rectangular plates arranged perpendicular to the velocity vector of the vehicle. Propulsive jets are applied at apogee of the transfer orbit in order to correct the decay of perigee and controlling the rate of heat transfer suffered by the vehicle during atmospheric passage. A PID controller is used to correct the deviation in the state vector and in the keplerian elements. The results show that aeroassisted transfer has a propellant consumption less than a Hohmann and bi-elliptic transfer.*

Keywords: *aeroassisted maneuvers, orbital dynamic, trajectory control.*

1 Introduction

At certain times of spacecraft mission, it is necessary to perform an orbital maneuver. To this, the spacecraft have to engage the thrusters or use the natural forces of the environment. The Hohmann transfer and Bi-elliptical transfer are alternatives to perform an orbit transfer by propulsive means. In 1961, Howard London presented the approach of using aerodynamic forces to change the trajectory and velocity of a spacecraft, this new technique became known as aeroassisted maneuvers (Walberg, 1985). This type of orbital transfer can be accomplished in several layers of the atmosphere; the altitude reached by vehicle is linked to the mission purpose and maximum thermal load supported by the vehicle structure.

The technique of using atmospheric drag to reduce the semi-major axis got known as aerobraking and was first used on March 19, 1991 by spacecraft Hiten. The launch was conducted by the Institute of Space and Astronautical Science of Japan (ISAS). The spacecraft passed through Earth's atmosphere at an altitude of 125.5 km over the Pacific Ocean at a speed of 11 km / s. The experience resulted in a decrease in apogee altitude of 8665 km. In May 1993, an aerobraking maneuver was used on a mission to Venus by Magellan spacecraft, whose goal was circularize the orbit of the spacecraft. In 1997, the probe U.S. Mars Global Surveyor (MGS) has used its solar panels as "wings" to control its passage through the tenuous upper atmosphere of Mars and lower its aposide.

There are several missions that become interesting with the use of aeroassisted vehicles, for example, reconfigure orbital systems that are unable orbital maneuvering (such as replacing a malfunctioning satellite by a spare), withdraw or transfer into a new orbit a space debris, operate Space Transportation Systems (STS), use atmospheric drag as a brake to provide the capturing of the vehicle, assist the International Space Station with the transfer of cargo between geostationary orbit (GEO) and low earth orbit (LEO), among others.

The main objective of the proposed technique, aeroassisted maneuvers, is fuel economy with respect to controlled maneuvering thrusters. This technique allows the reduction of the vehicle orbital energy using atmospheric passages. According to Walberg (1985), many papers on aeroassisted orbital transfer have been made in recent decades and have been shown that a significant reduction in fuel can be achieved using aeroassisted maneuvers instead of Hohmann transfer. Consequently, the reduction of fuel provides an increase in payload capacity of the vehicle. The use of aerobraking maneuver in the NASA space mission of the Mars Odyssey reduced the mass of the spacecraft in more than 200 kg (Tartabini et al., 2005). Future missions to Mars, even manned missions that are being planned, should use this technique to take advantage of the benefits generated.

Within a national context, we can cite the project's scientific micro-satellite Franco-Brazilian (FBM), a partnership between the Brazilian and French space agency (INPE and CNES), which would be released as a ride on an Ariane 5, and then would perform aerobraking maneuvers to transfer the satellite to the orbit service (Furlan, 1998). The Ariane 5 rocket has the capacity to carry up to eight microsatellite with a maximum individual weight of 120 kg through the platform Ariane Structure for Auxiliary Payload (ASAP). However, the rocket was designed to place satellites in geostationary orbits. The propellant required to transfer the FBM to a low orbit (between 800 and 1300 km) by means of chemical propellants, would exceed the allowed amount of mass. This question has led the space agencies to study the concept of aerobraking as a workaround. CNES in 2003 left the program which was subsequently discontinued (Brezun et al., 2000).

2 Aeroassisted transfer description

This study aims to examine the effects that an aeroassisted maneuver around the Earth, can cause in the orbital elements. It also aims to demonstrate the difference in fuel costs and the transfer time elapsed between an aeroassisted maneuver and a fully propulsive maneuver. The geometric shape of the spacecraft used in aeroassisted transfers is an important parameter that can increase the overall efficiency of the maneuver. In this paper we adopted a spacecraft with a cubic body composed of two rectangular plates, called aerodynamic plates, placed in opposite sides of the vehicle body. The inclination angle of the plates with respect to the molecular flow is called of attack angle, whose value has been placed at 90 degrees to maximize the projected area and the drag force.

We intend to demonstrate the simulation of an aerobraking maneuver between geostationary orbit and low orbit. The orbits are considered circular and coplanar. First, it applies an impulse to take the vehicle out of the geostationary orbit and put it into an elliptical orbit with perigee within the limits of the atmosphere. After each passage by atmospheric region, occurs the reducing of the apogee of the transfer orbit. When the spacecraft reaches the final apogee altitude, then, a new impulse is applied to the vehicle to remove it from the transfer orbit and insert it into the final orbit. In order to control the rate of heat transfer suffered by the vehicle during passage through atmosphere, propulsive jets are applied at the apogee correcting the decay of perigee. This transfer strategy is shown in Figure 1.

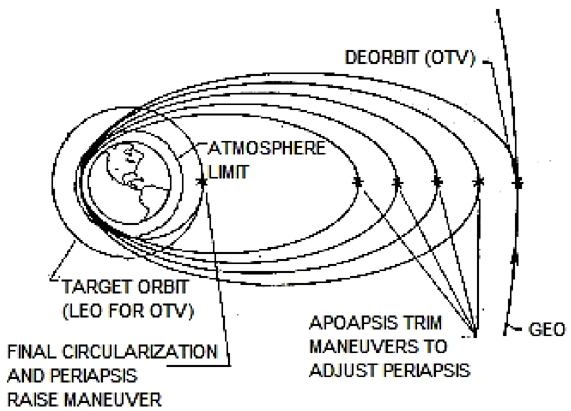

Figure 1. Multipass aeroabraking.
Ref.: Adapted by Walberg (1985).

3 Aeroassisted transfer equations

The main forces acting on a spacecraft in orbit are: gravitational force (*mg*), thrusters force (T_s) and aerodynamic forces (*F*) caused by the interaction with the atmosphere. The spacecraft position in space determines the magnitude of aerodynamic forces suffered by the spacecraft. A planet with an increased atmospheric density will generate higher aerodynamic forces. The aerodynamic force can be divided into two: the drag force (F_D), whose direction is opposite to the velocity vector and lift force (F_L), perpendicular to the drag force. According to Vinh (1981), the magnitude of these forces is given by the following equations:

$$F_D = \frac{1}{2}\rho S V^2 C_D \tag{1}$$

$$F_L = \frac{1}{2}\rho S V^2 C_L \tag{2}$$

where ρ is the atmosphere density, C_D and C_L are, respectively, the drag and lift coefficients on the projected area S and V is the velocity of the spacecraft relative to the atmosphere. The lift can also be decomposed into altitude lift force (F_A) and lateral lift force (F_B). The attack angle (α) is measured between the longitudinal axis of the spacecraft and the velocity relative to the atmosphere. The magnitude of the aerodynamic force depends mainly on the attack angle, and its direction varies depending on the bank angle (σ), whose angle is between the lift plane and the plane formed by the velocity vector on the atmosphere and vector position of the spacecraft, as shown in Fig. 2.

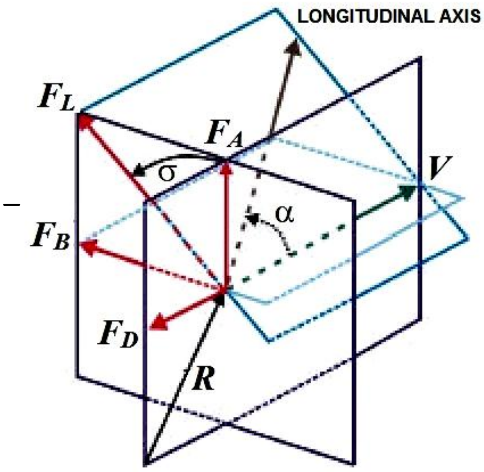

Figure 2. Components of the aerodynamic forces, attack angle and bank angle.
Ref.: Guedes (1997).

The directions and amplitudes of these forces can be calculated by the following equations (Guedes, 1997):

$$\vec{F}_D = -F_D \hat{V} \tag{3}$$

$$\vec{F}_L = F_A \hat{N} + F_B \hat{H} \tag{4}$$

where

$$F_A = \frac{1}{2}\rho S V^2 C_A \tag{5}$$

$$F_B = \frac{1}{2}\rho S V^2 C_B \tag{6}$$

$$\hat{V} = \frac{\vec{V}}{\left|\vec{V}\right|} \tag{7}$$

$$\hat{H} = \frac{\vec{H}}{\left|\vec{H}\right|} \tag{8}$$

$$\hat{N} = \frac{\vec{N}}{\left|\vec{N}\right|} \tag{9}$$

$$\vec{H} = \vec{R} \times \vec{V} \tag{10}$$

$$\vec{N} = \vec{V} \times \vec{H} \tag{11}$$

The drag coefficient (C_D), altitude lift (C_A) and lateral lift (C_B), are calculated using the Impact Method (Regan and Anandakrishnan, 1993), according to the following equations:

$$C_D = 2\,\mathrm{sen}^2\alpha \tag{12}$$

$$C_L = 2\,\mathrm{sen}\alpha\cos\alpha \tag{13}$$

$$C_A = C_L \cos\sigma \tag{14}$$

$$C_B = C_L\,\mathrm{sen}\sigma \tag{15}$$

The Impact Method assumes an elastic reflection of particles in a specular surface. The normal component of impact velocity is reversed while the tangential component is unchanged. This model assumes that the particles have no random velocity component usually associated with microscopic particle of gas (Regan and Anandakrishnan, 1993).

The atmospheric model U.S. Standard Atmosphere provides the value of the atmospheric density, depending on the position of the vehicle, for the calculation of aerodynamic forces. The velocity of the spacecraft relative to the atmosphere in the inertial system is calculated assuming that the atmosphere has the same rotation velocity of the Earth and its equation is given by Kuga et. al. (2000):

$$\vec{V} = \dot{\vec{r}} \times \vec{r} = \begin{bmatrix} \dot{x} + wy \\ \dot{y} - wx \\ \dot{z} \end{bmatrix} \tag{16}$$

where $\dot{\vec{r}}$ is the velocity vector relative to the inertial system and $\vec{w}$ is the angular velocity vector of Earth's rotation.

Some of the major difficulties faced by the spacecraft during atmospheric maneuver are related to the increase of heating rate and reduction of velocity. These quantities increase as the vehicle suffer high atmospheric densities and high velocities. In the upper atmosphere, it should be considered a form of heating known as free molecular heating. This phenomenon occurs due to the impact of free molecules with the vehicle. The rate of heat transfer per area unit is given by the following equation (Gilmore, 1994):

$$\dot{Q} = \frac{1}{2}\alpha_c \rho V^3 \tag{17}$$

where α_c is the coefficient of thermal accommodation (Gilmore (1994) recommends using a value of 1).

4 Architecture of the aeroassisted maneuver simulator

The control of modern plants, processes and systems require the development of complex models and simulators, often reflecting the relations representative of the phenomena in progress for many lines of computer code. A trajectory simulator of a spacecraft, called Spacecraft Trajectory Simulator (STS), was developed by Rocco (2006), using the approach of modeling and simulation of information flow in *Matlab / Simulink®* software. Based on the STS, we developed the Aeroassisted Spacecraft Maneuver Simulator (SAMS). This simulator considers a reference trajectory and a trajectory perturbed by external disturbances combined with non-idealities of sensors and actuators. It is able to operate in closed loop controlling the trajectory at each instant of time, which is one of the input parameters, using a PID controller and propulsive jets.

5 Results

This section aims to present the results of an aeroassisted maneuver simulation to transfer the spacecraft from geostationary orbit to low orbit of 1000 km of altitude. The graphics to be presented are referred only to the aeroassisted transfer. Table 1 shows the initial conditions of the orbit.

Table 1. Initial condition of the transfer orbit.

Description	Value	Units
Apogee altitude	35786.14	km
Perigee altitude	115	km
Eccentricity	0.7332	-
Inclination	1	degrees
RAAN[1]	200	degrees
Perigee argument	10	degrees
Mean anomaly	180	degrees

Note: [1] Right Ascension of Ascending Node

The complete maneuver was performed in 58.93 days and, at the end of that period, there was a reduction of approximately 35,000 km in the apogee altitude (Figure 3). The perigee altitude remained at an average of 115 km with a variation of ± 0.5 km due to the application of jet propulsion at the apogee of the orbit (Figure 4).

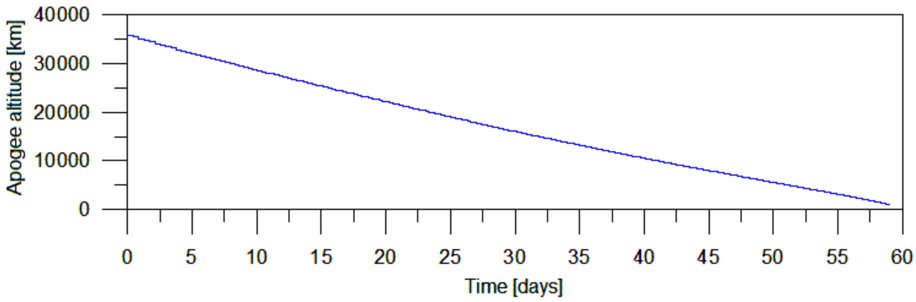

Figure 3. Apogee altitude as function of time.

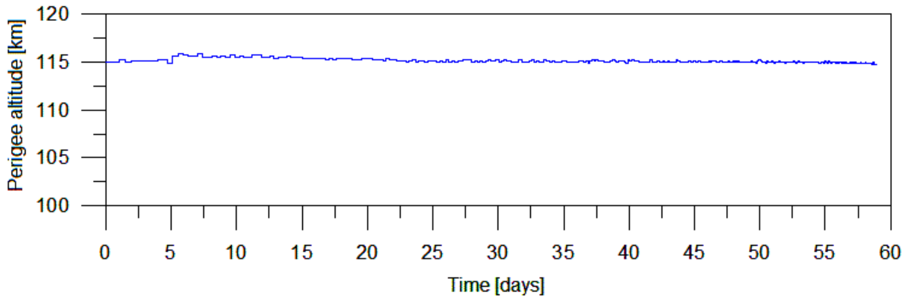

Figure 4. Perigee altitude as function of time.

There was no change in the orbit inclination because lift forces were not being applied to the vehicle. Figure 5 illustrates the deviation of the semi-major axis versus time. This divergence is due to limitations and non idealities of the thruster, causing a deviation between the reference trajectory and the disturbed trajectory. During the maneuver, the control system acts to reduce this divergence. The error appears when the first jet propulsion is applied in the apogee.

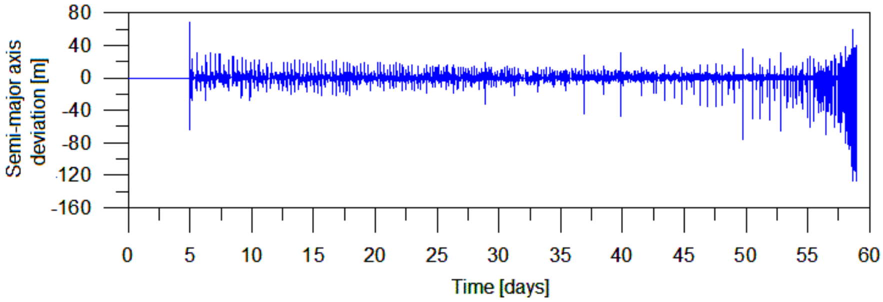

Figure 5. Semi-major axis deviation as function of time.

Figure 6 shows the variation in the X, Y and Z components of the position vector for the early days of the maneuver. The variation almost zero at the Z component is due to be roughly an equatorial orbit. The behavior of curves in X and Y components is related to the eccentricity of the orbit. As the vehicle approaches the perigee of the orbit the orbital velocity increases, and vice versa.

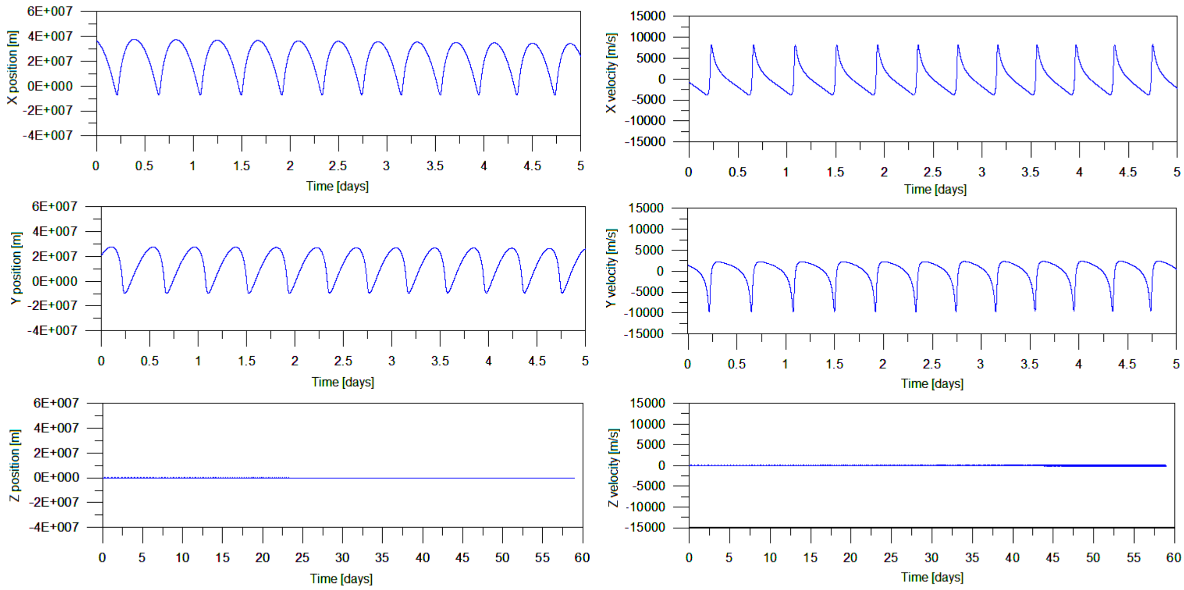

Figure 6. X, Y and Z components variations of the position and velocity vector as function of time.

The propulsive thrust applied at the apogee of the orbit versus time is shown in Figure 7. The circularization of the orbit increases the crossing through the atmosphere and the decay of the perigee altitude. The thrusts of lesser magnitude are applied to correct deviations in the trajectory, while those of greater magnitude are to correct the decay of perigee.

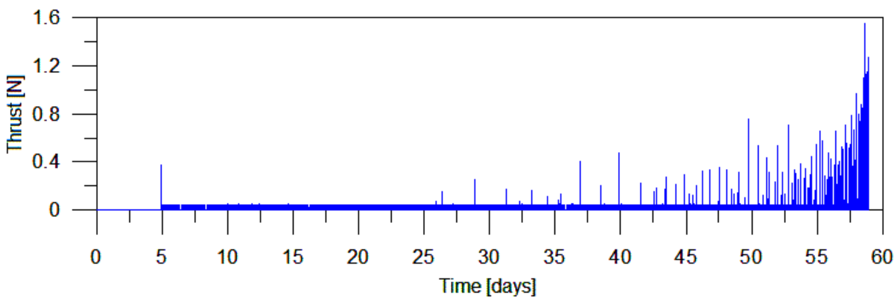

Figure 7. Propulsive thrust as function of time.

Figure 8 illustrates the drag force suffered by the vehicle during crossing through the atmospheric region. It can be observed a downward trend at the end of the maneuver. This behavior is related to the velocity reduction and with the circularization of the orbit.

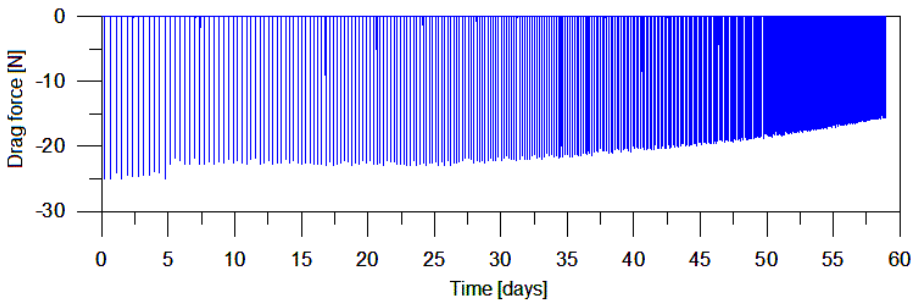

Figure 8. Drag force as function of time.

The rate of heat transfer suffered by the vehicle as function of time is shown in Figure 9. The maximum value supported by the vehicle depends on the material structure. The values obtained are within the limit given by Tewari and Kumar (2005). However, the rate of heat experienced by the vehicle can be controlled by controlling the decay of the perigee altitude; the lower altitude will be higher rates of heat suffered by the vehicle.

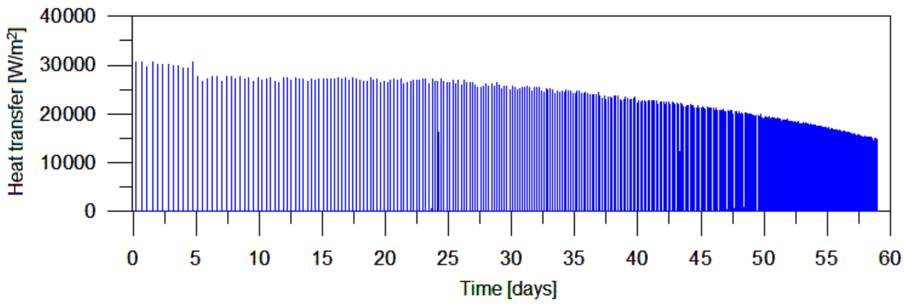

Figure 9. Rate of heat transfer as function of time.

Regarding consumption of propellant, two situations are considered. The first illustrates a hypothetical situation: it is considered that the drag force suffered by the vehicle is provided by the propulsion system (Figure 10) and the second situation illustrates the case that considers only the real thrust to correct the decrease in perigee altitude (Figure 11).

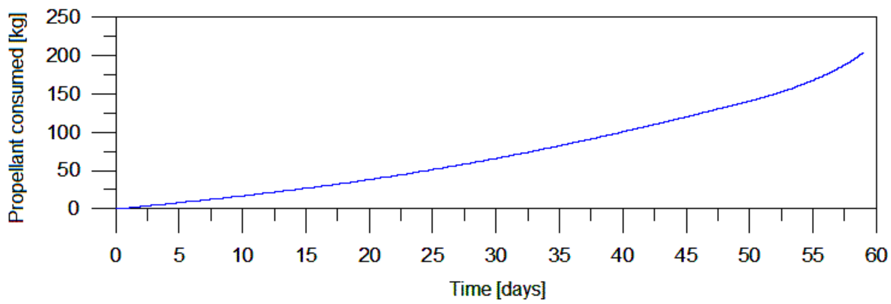

Figure 10. Hypothetical situation: propellant required for applying a thrust equal to drag force.

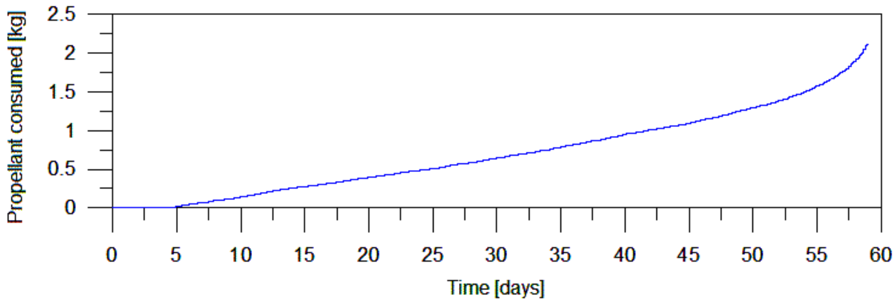

Figure 11. Real situation: propellant necessary to correct the decay of perigee.

To perform the same maneuver using only the propulsion system, with application of thrust at perigee of the orbit transfer, and given the same magnitude of drag force, would be consumed approximately 200 kg of propellant. In the second case, in which the propulsion system was used only to correct the decay of perigee, was consumed approximately 2.11 kg of propellant. Although this is a low value, it should take into account that the propellant takes to enter and exit the transfer orbit.

Figure 12 shows a comparison between the consumption of propellant transfer Hohmann, Bi-elliptic transfer and aeroassisted maneuver. In this case, it was considered the consumption of propellant to enter and exit of the elliptical orbit transfer. The aeroassisted maneuver spent 2.11 kg of propellant to correct the decay of perigee and 158.81 kg to enter and exit of the transfer orbit. The fuel economy of aeroassisted maneuver related on the transfer of Hohmann was approximately 116 kg

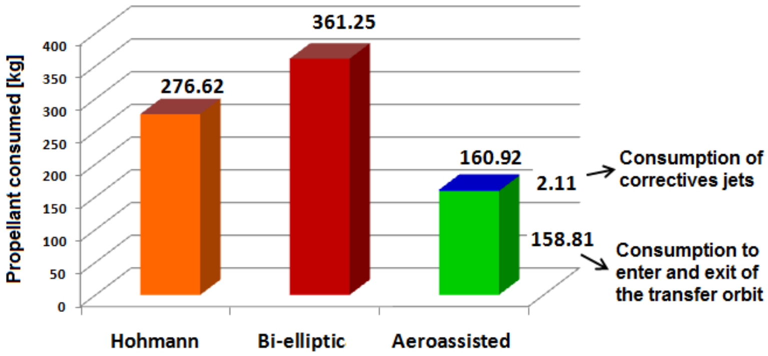

Figure 12. Comparison of propellant consumed between propulsive and aeroassisted maneuvers.

Finally, Figure 13 shows a comparison of time needed to transfer the vehicle from geostationary orbit to low earth orbit using a Hohmann transfer, Bi-elliptic or aeroassisted maneuver. The aeroassisted maneuver took 58.93 days to reach the final orbit, while the transfer of Hohmann and bi-elliptical, required far less time, 0.22 and 1.48 days respectively. It was considered the ideal case for calculating the transfer time of propulsive maneuvers, but when we consider the real case in which thrust is applied to smaller magnitude due to the limitations of the propellant, and a number of propulsive maneuvers to reach the final orbit, the time to perform the maneuver increases.

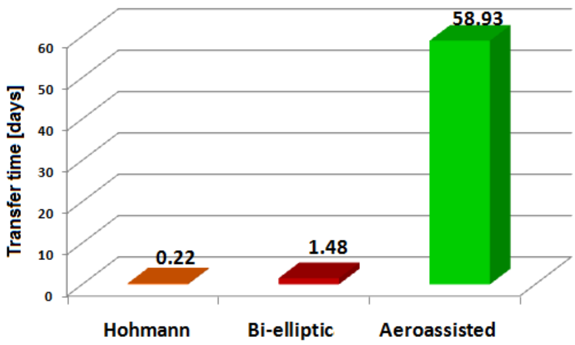

Figure 13. Comparison of transfer time between propulsive and aeroassisted maneuvers.

6 Conclusions

It was presented the simulation of a aeroassisted maneuver to transfer the vehicle from geostationary orbit to low orbit about 1000 km altitude using propulsive jets to correct the decay in perigee altitude and correct deviations between the reference trajectory and the disturbed trajectory. It can be concluded that the control system managed to meet expectations since it managed to maintain the residual error in state vector, where the thrusts was applied, within acceptable limits.

The corrective propulsive jets allowed maintain the perigee altitude within reasonable limits (115 km ± 0.5 km), causing the vehicle had not suffered high thermal loads during the crossing through the atmospheric region. This case can be compared to the mission of scientific micro-satellite Franco-Brazilian (FBM), in which there was a need to transfer the satellite from geostationary orbit to low orbit and aeroassisted maneuvers could be used.

In general, the aeroassisted maneuvers were more advantageous in terms of fuel economy than the fully propulsive maneuvers. It was also concluded that use of the control system closed loop was critical to the success of the simulations, without which it would not be possible to eliminate the residual errors in the trajectory efficiently.

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